Introducing Concentrating Solar Power Technologies to the Northeastern University Engineering Curriculum

Presented by:

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Co-Investigators

Prof. Hameed Metghalchi

Prof. Yiannis Levendis

November 20, 2024

HelioCon Seminar Series

Solar Power Plant at Themis (Textbook Figure 1.3)

Introduce students/practitioners to the challenges of CSP

- How to analyze system performance?
- How to design CSP systems?
- How to operate?

Figure 1.4. *Solar furnace of CNRS at Odeillo-Font-Romeu. In the foreground, the dish–Stirling module being tested*

At the top of NREL's South Table Mountain campus, the HFSF is a unique user facility for testing high-

Solar Power Plant at Themis (Textbook Figure 1.4)

NORTHEASTERN UNIVERSITY

Northeastern University is a private R1 University located in Boston

- ❑ 15,891 Undergraduates
- ❑ 15,268 Graduate students (Both Ph.D and MS students)

One unique feature is that it is a cooperative education (co-op) curriculum

- ❑ Over 90% of the undergraduate participate in this program
- ❑ Students after their first year rotate 6 months in class and 6 months in a practical setting
- ❑ Most Industrial co-op positions are an identified position in the company and reflects the academic progress of the student

Additional Certificate programs such as the Gordon Engineering Leadership program are available to graduate students at the MS level

Department of Mechanical and Industrial Engineering

Approximately 600 Undergraduate students in both Mechanical and Industrial Engineering programs

Traditionally, Material Science is in the Department

The Department has

- ❑ 65 tenure track faculty
- ❑ 20 professional teaching faculty

Within the Department are several professional MS graduate programs

- ❑ Energy Systems
- ❑ Engineering Management
- ❑ Operation Research
- ❑ Mechatronics

We at NU are positioned to participate as CSP educational providers and to introduce large number of students to this field

Our Approach has been to leverage several educational opportunities within our curriculum

CSP Graduate Course (One Objective of the HeliCon Grant)

Capstone (Senior) Design Projects (Spans two terms, 21 weeks, a constructed prototype)

Develop Short Courses for practitioners in CSP

Undergraduate and Graduate research projects

LSAMP Summer Programs participation

Develop Co-Op opportunities

Special Topics Course ME 5374
“APPLICATIONS OF CONCENTRATING SOLAR THERMAL TECHNOLOGIES”
Spring 2024

Prof. Greg Kowalski

University Approved Course:

ME5680: APPLICATION OF CONCENTRATED SOLAR POWER

Offered: Spring 2025, On ground and Online

At the top of NREL's South Table Mountain campus, the HFSF is a unique user facility for testing high-

Figure 1.3. *Thémis, operating solar power plant (Targasonne, 66)*

Course Operation

The course is being offered as a Special Topics course because it is new and the topic is at the edge of new technology. For these reasons the course will be conducted in a seminar manner where there will be assigned reading and research topics on a weekly basis. We meet remotely once a week and this meeting will be recorded and distributed afterwards to all students in the course. The time will be determine based on your collective availability. During this remote meeting the format will be:

- **Address questions from the readings and assignments.**
- **Open discussion of the readings: do you agree with all the statements in the reading, what questions did you formulate based on the reading, how does your experience coordinate with the readings.**
- **Short lecture material to fill in background or clarification of the readings.**
- **In some classes I will ask a student to present their work and moderate the discussion. The student will be for worn before the class.**

We will meet remotely once a week to discuss the assignments with a student assigned to present their work to begin the discussion. The weekly assignments will also include homework; some very direct type problems and others a bit more open-ended.

Course Objectives

At the conclusion of the course, the student should be able to:

- ❑ Understand the difference between power and energy performance measures and their
- ❑ differences as related to the supply and load views
- ❑ Determine the benefits of CSP as related to power producing or manufacturing
- ❑ capabilities related to the high temperatures achieved in these systems
- ❑ Predict incident solar radiation at a CSP site
- ❑ Simulate the geometric optics to determine the incident radiation on the tower receiver
- ❑ Predict performance measures of the heliostat fields
- ❑ Predict the thermal performance of the receiver
- ❑ Predict performance of Thermal Storage as it relates to the performance measures
- ❑ Understand the economics of CSP system, including storage
- ❑ Sustainability issues relating to the second law and thermoeconomic considerations

Textbook "Concentrating Solar Thermal Energy: Fundamentals and Applications", Gilles Flamant, Wiley, 2022

Chapter 1, Solar Power Plants: State of the Art
Chapter 2, Solar Resource Management, Assessment and Forecasting
Chapter 3, Optics of Concentrating Systems
Chapter 4, Solar Receivers
Chapter 5, Heat Transfer Fluids for Solar Power Plants
Simulation, need for numerical methods (Material Similar to Chapter 6)
Chapter 7, Materials for Concentrated Solar Power
Chapter 8, Thermal Energy Storage (Simulation)
Chapter 10, Synthetic Fuels from Hydrocarbon Resources
Chapter 11, Solar Fuel Production by Thermochemical Dissociation of Water and Carbon Dioxide
Microeconomics and thermoeconomics
Manufacturing Potential of Concentrating Solar Power

What was effectively accomplished(First time, setting):

Red Highlight: Briefly discussed
Yellow Highlight: Discussed, no assignment

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Chapter 2, Solar Resource Management, Assessment and Forecasting
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Chapter 10, Synthetic Fuels from Hydrocarbon Resources
Chapter 11, Solar Fuel Production by Thermochemical Dissociation of Water and Carbon Dioxide
Microeconomics and thermoeconomics
Manufacturing Potential of Concentrating Solar Power

Recommended References (Nine Given)

"Concentrating Solar Power Technology Principles, Developments and Applications", Volume in Woodhead Publishing Series in Energy: Book 2012
Editors: Keith Lovegrove and Wes Stein, Science Direct

"Advances in Concentrating Solar Thermal Research and Technology", (Woodhead Publishing Series in Energy) 1st Edition, Manuel Blanco (Editor)

"The Economics and Policy of Concentrating Solar Power Generation", Pere Mir-Artigues, Pablo del Rïo, Natïlia Caldïs, 2019, Springer International Publishing

"Heliostat Fields: A Classical Approach to Analysis and Layout Optimization", 2016, Shanley Lutchman,,

"Renewable and Efficient Electric Power Systems, 2nd Edition", Masters, 2013, John Wiley & Sons

"Fundamentals of Engineering Thermodynamics", Moran and Shapiro, 4th or higher edition, John Wiley & Sons

"Thermodynamics: An Engineering Approach", Cengel & Boles, 3rd or higher editions, McGraw-Hill

"Energy Systems Engineering Evaluation and Implementation, Vanek, F.M. and Albright, L.D., McGraw Hill, New York, 2008

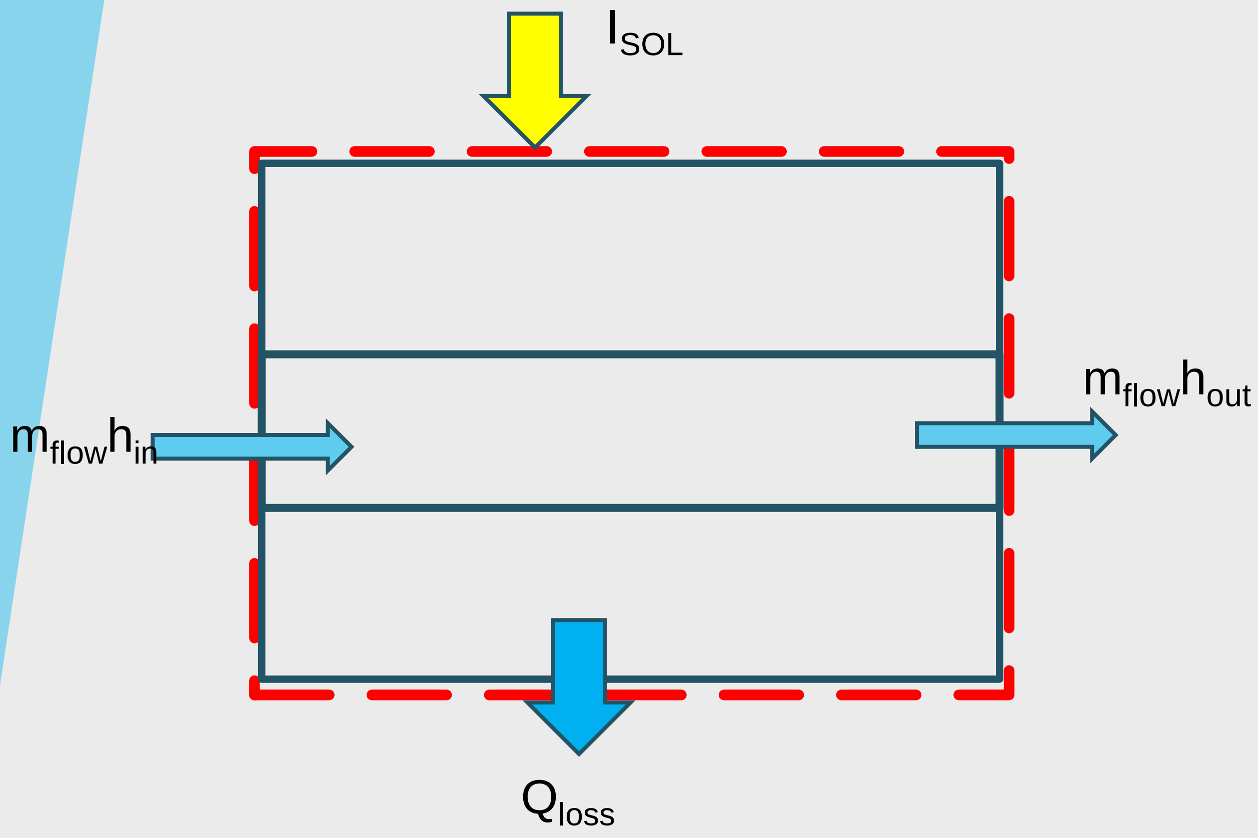
"Introduction to Heat Transfer", by Incropera, DeWitt, Bergman & Lavine, Fifth Edition, John Wiley & Sons.

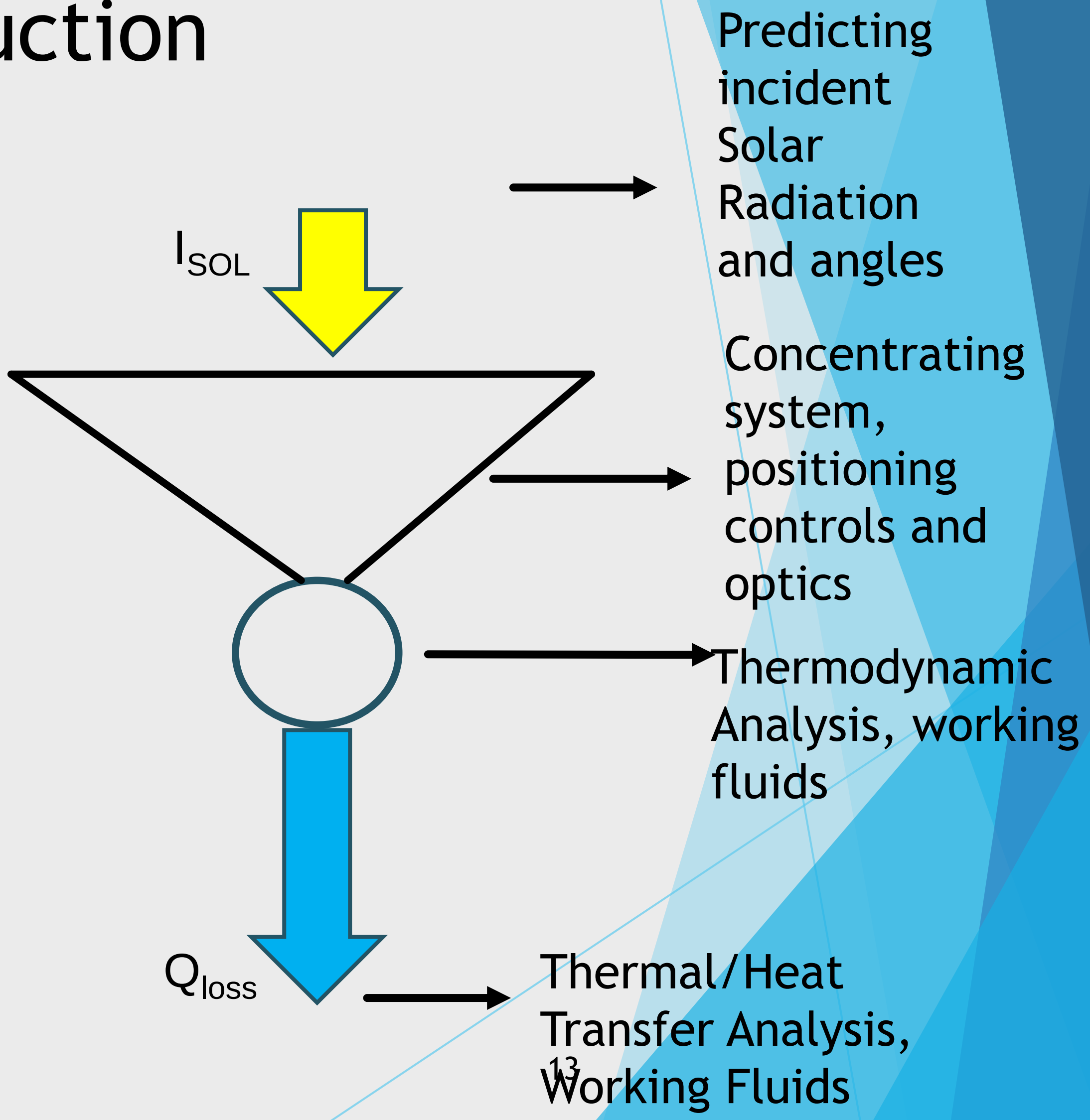
Sample Homework (Assignment 2)

You have been given the following single point design condition for direct incident solar radiation on the collector of 550 W/m^2 and a surrounding temperature of 18 C You can perform your analysis at steady state conditions. Determine the power output and first law efficiency of the concentrating solar power (CSP)system.

The CSP will heat the working fluid from a temperature of 32 C and has a concentration factor of 10,000. The concentration factor is the ratio of the incident solar radiation on the collector to the incident solar radiation area where it is absorbed. The optical efficiency of this system is 0.94 and the solar absorptivity of the receiver is 0.98. Note: that defining your system at the incident area will avoid needing the geometric optics information associated with the concentration factor. The concentrating collector has an opening of 5 m2 and a heat transfer area of 0.05 m2 for the receiver. The mass flow rate of the working fluid through …………………..

System Definition for Assignment 2: Future Topics Introduction





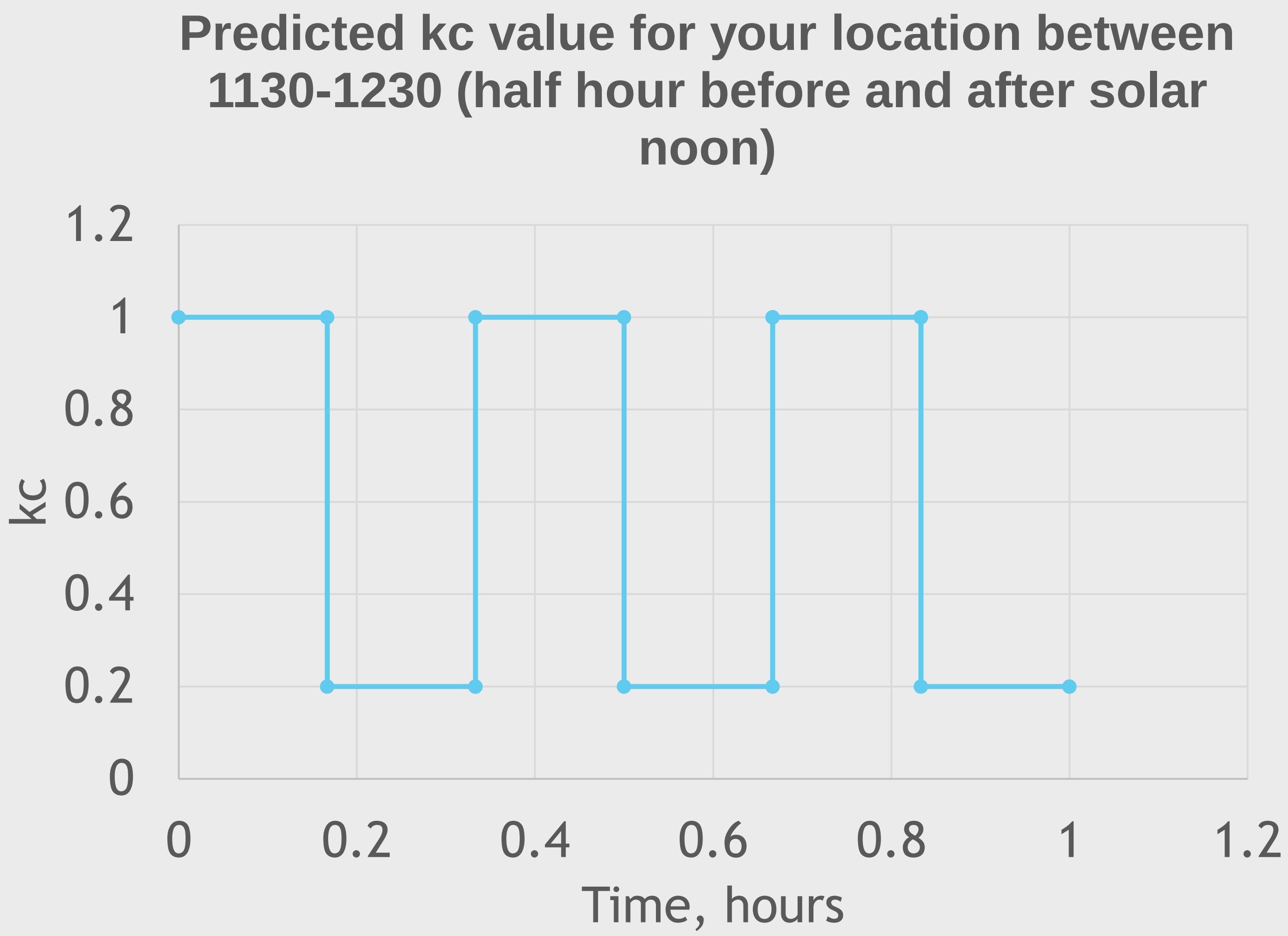
NOT SHOWN: Power producing cycle, manufacturing process and energy storage systems

Sample Homework (Assignment 4)

4.1 You are operating a CSP plant as described in Homework 2 in your home location. You have received the following information for the k_c (Cloudiness factor) (see graph below) for July 15 for the time 11:30-12:30, where 12:00 is solar noon. Assuming that you can neglect transient heating effects, the quasi-steady state assumption, calculate the produced energy from your CSP plant for this one hour period and compare it to the amount of energy you would produce using the incident solar radiation based on the clear sky estimates for half hour estimates. This assignment combines Assignment 3, the incident solar calculator, and the material in Chapter 2. The integration of the weather prediction, the k_c value, and the simulation model and the corrections made to your assignment 2, allow you as the operator to inform the electric grid operators of the energy you will be providing for this one hour period. This information is important for you and the electric grid operators in order to satisfy the load demand for that hour.

Introduces the difference between the design of the CSP system and operating it using weather data. Also integrates several topics and exposes them to the simulation process

Sample Homework (Assignment 4)

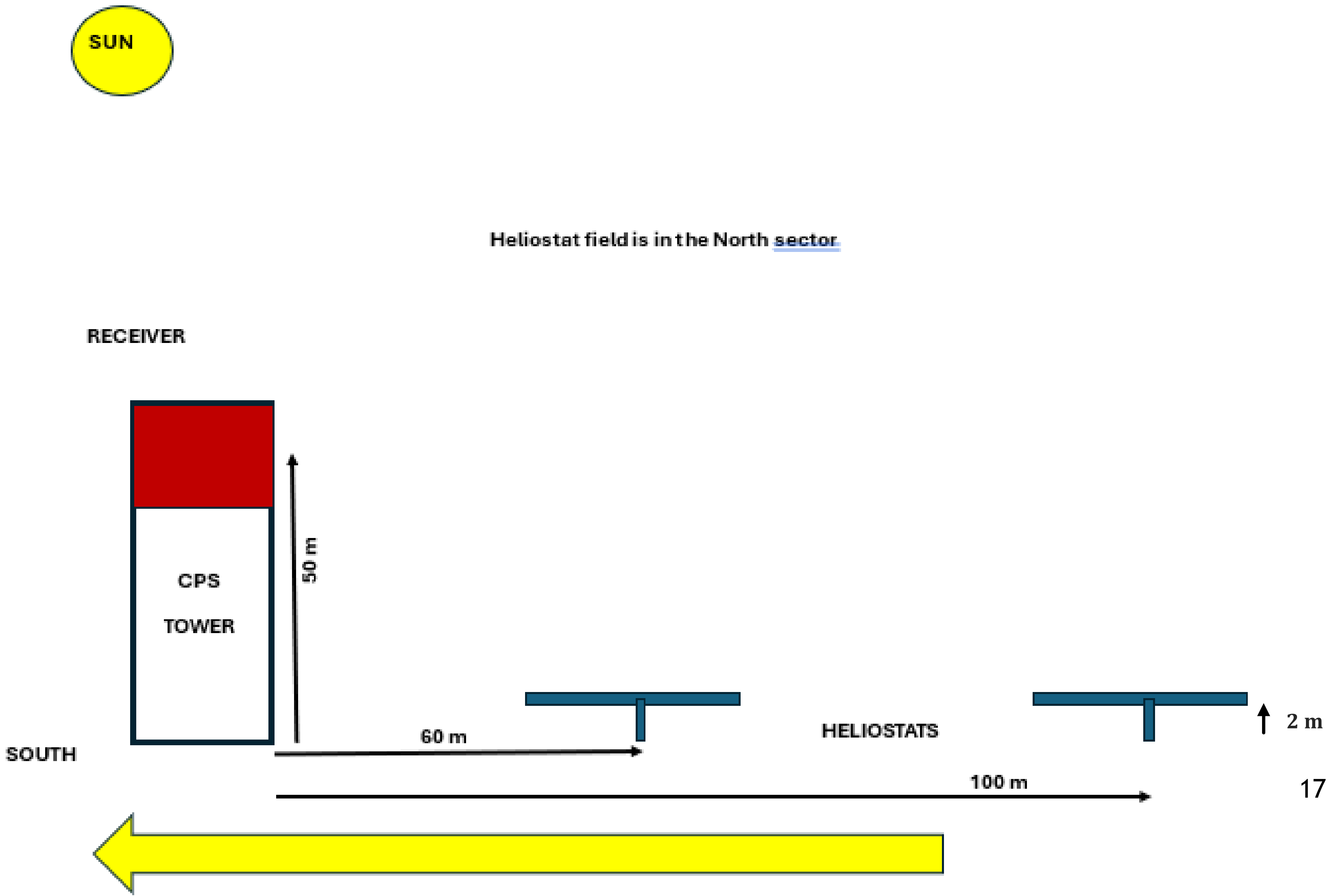


Sample Homework (Assignment 4.3)

4.3 In the sketch below the position of two heliostat mirrors are shown relative to the CSP tower and the center of the receiver volume. The heliostat mirrors are shown in their horizontal position to illustrate their relative location. The CSP tower and mirror centers are in a common line pointing due south, ie at solar noon the tower and two heliostats will lie on common line with the sun. The position of the sun in the drawing is also arbitrary for the sake of illustration and all heliostats are in a northern field. The mirrors measure 3 x3 m, an area of 9 m^2. The center of the mirror is located 2 m from the horizontal plane at the foot of the tower. Calculate the azimuth and zenith angle that these collectors must be positioned in order to focus the image of the sun onto the receiver surface for your home location at the following times: 10:00, 12:00 (solar noon) and 1400 hours. You can assume clear sky radiation, a k_c = 1value, a mirror reflection of 0.96 and that the solar receiver is cylindrical in shape and large enough to accommodate the reflected image of the sun. The incident beam radiation can be considered to be parallel rays. ………..

Introduces the difference between the design of the CSP system and operating it using weather data. Also integrates several topics and exposes them to the simulation process

Geometry for problem 4.3



Sample Homework (Assignment 5)

5.1 In a receiver tube design similar to Fig. 4.1 pressurized water flows at a mass rate of 0.9 kg/s. The specific heat of water can be considered as constant for this calculation at a value of 6000 J/(kg K). The incident solar radiation on the concentrator is 800 W/m^2 and the area is 4 m^2. Note: The incident solar radiation represents the peak value for this system and the performance will provide the peak power production. The concentration factor for the field is 250 (linear concentrator) and the optical efficiency is 0.92. The tube is made of Inconel with a thermal conductivity of 11.4 W/(m K), outer diameter of 0.080 m, an inner diameter of 0.075 m and a length of 1 m. In this CSP design two tubes are used in series to heat the working fluid. The solar absorptivity of the tube is 0.95 and the long wave emissivity is 0.2. ………………………………

Introduces combined radiation and convection calculations, radiation band width models and applying fundamental numerical analysis (2 tubes in series) Also, iteration starting with linearizing radiation.

Chapter 4 provides a good example of using fundamental numerical analysis for receiver design

Figure for Problem 5.1

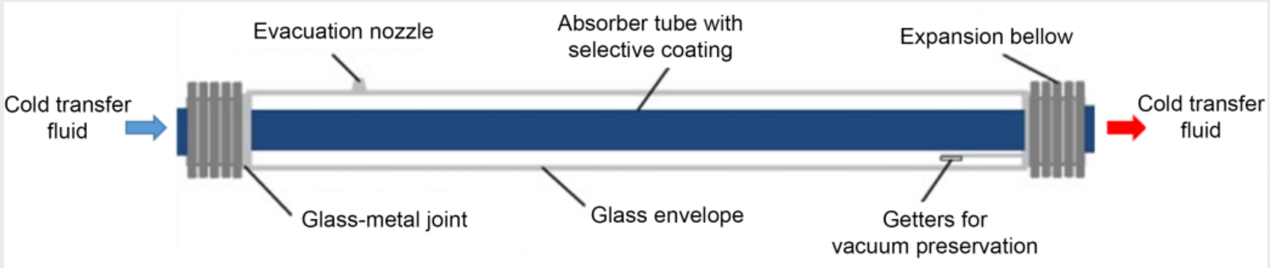


Figure 4.1. *Schematic representation of an absorber tube and its components (Espinosa-Rueda et al. 2016)*

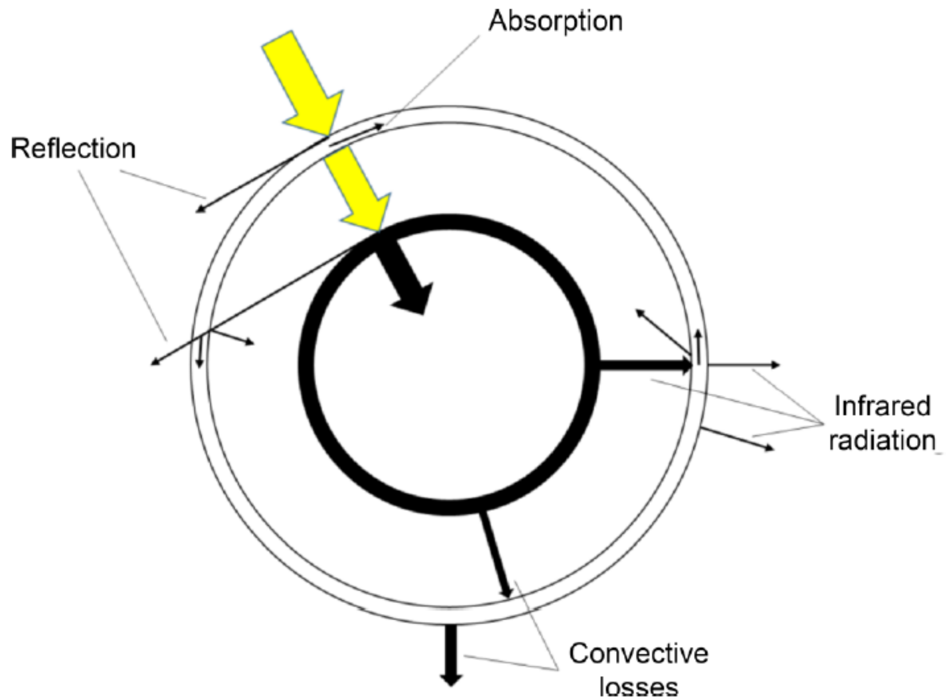


Figure 4.2. *Thermal phenomena in an absorber tube*

Course Outcome Review

- Course Attendance remains constant, 85% (small numbers and 2 students had conflicts with set meeting times). Sessions are taped and made available to all enrolled students
- Homework submission is 100
  - Assign. 1 100%
  - Assign. 2 75% (New background material, review of previous coursework)
  - Assign. 3 100% (Using provided code)
  - Assign. 4 70% (Ray tracing-new material to most)
  - Assign. 5 85% (Basic energy balance and identifying radiative transfer boundaries)
- Exams: Midterm: 83.8 Final: 76.0
- Mixed feelings as for first offering, learned what the students need.
- Mode of course offering differs significantly from the On Ground mode

urse Outcome Summary /Starting point for Spring 2025

- Survey on Geometric optics/Ray Tracing 0% had been exposed to it during their education. (I'm not surprised)
  - Homeworks 4 and 5 confirmed this weakness
  - Midterm exam also confirmed weakness, reason for a special lecture based on homework 4
  - Saw some improvement on final exam in part of the class, another student segment seemed to not apply material presented and I want to try different approaches
- Basic radiation theory, solid angles, iterative solution, and geometric interpretation seem to be common weakness
  - Homework 5 and Final exam illustrated basic approach weakness.
- Numerical methods: Final indicated a background weakness, even though the book had a good discussion of design specific approach.

Hand off to Prof. Umit Coskun is occurring for on ground/online course.

Has experience with our students and identified background weakness that he will address

Expand background materials

Our Approach has been to leverage several educational opportunities within our curriculum

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Item 2: Involvement of undergraduate students in Capstone Senior Design Projects relevant to Heliostats

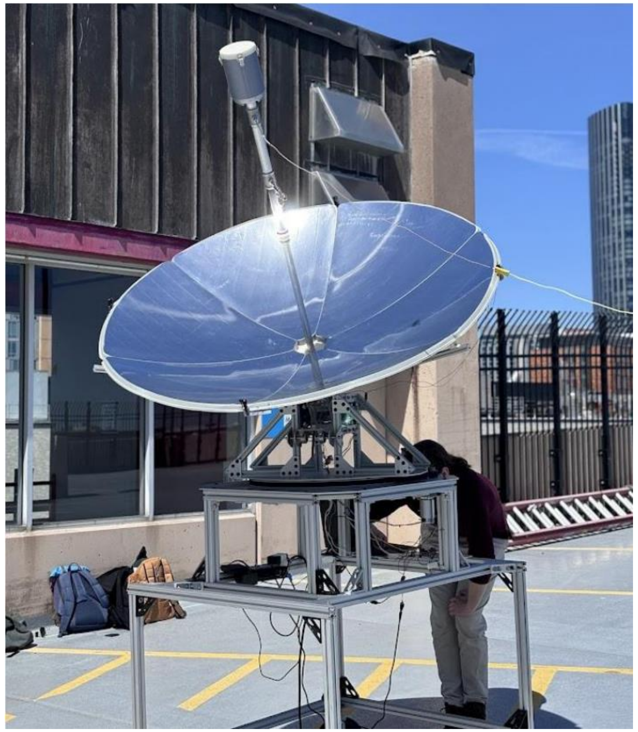


Figure 3: Solar Pyrolizer Dish testing

CSP Project #3: Solar Pyrolizer Dish (Phase II)

- **Objective**: to update the feeding system and solar tracking capabilities of a solar pyrolizer dish meant to turn dried pine needles into biochar
- **Design**: redesigned hardware and circuitry; advanced auger feeding system used to control pine needle flow rate
- **Results**: preliminary testing showed temperatures of 550 degrees Celsius reached – continued testing needed for auger system

Heliostat Mirror Project Phase II

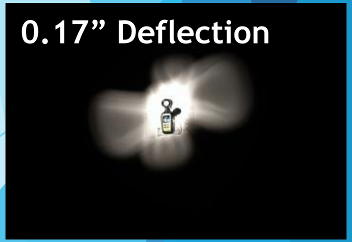
Design a light-weight MirrorED, DEORMABLE SURFACE with a highly effective FACET

Advisor: Yiannis A. Levendis y.levendis@neu.edu
Co-advisor: Greg Kowalski gkowal@coe.northeastern.edu

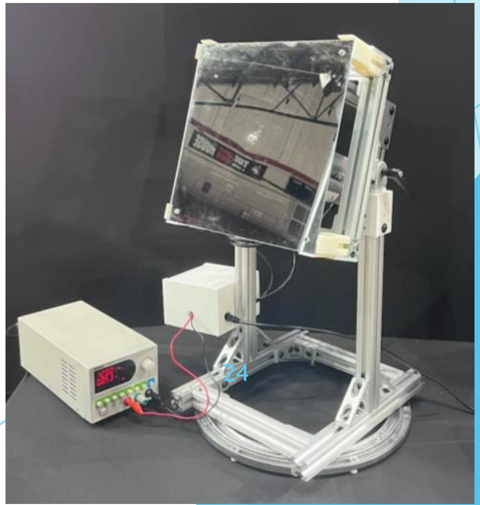
Summer I, 2024

Heliostats comprise static and dynamic components (reflective area, a control system, and the mounting and tracking mechanism) operating in a highly controlled manner to provide accurate solar flux pointing and concentration. They are primarily used in solar tower applications that provide high energy flux and temperatures (500° – 2000°C) that can lead to more efficient solar collection for electrical power production and energy storage. One of the active areas of research is on how to improve the astigmatic aberrations of focusing light from the heliostat mirrors to the target on the tower, see figure below.

Phase 1 designed and constructed a deformable heliostat mirror, see below. They tested it and found possibilities tor attaining concentration of reflected light on a smaller area to the target, see below. Phase II is needed to improve on the focusing the reflected sunlight on the target and implementing a method for simultaneously tracking the sun and its reflection on the target. In addition, combining these improvements into a matrix of mirrors (at least four) using the novel means of deformation has the potential cost and control strategy benefits.



https://www.energy.gov/eere/solar/articles/no-smoke-all-mirrors-developing-next-generation-heliostats



Heliostat SUN and Tower tracking project, PHASE II

Design a solar tracking system for a heliostat mirror

Advisor: Yiannis A. Levendis y.levendis@northeastern.edu
Co-advisor: Greg Kowalski gkowal@coe.northeastern.edu
Summer I, 2024

Heliostats comprise static and dynamic components (reflective area, a control system, and the mounting and tracking mechanism) operating in a highly controlled manner to provide accurate solar flux pointing and concentration. They are primarily used in solar tower applications that provide high energy flux and temperatures (500° – 2000° C) that can lead to more efficient solar collection for electrical power production, conversion of waste materials to fuels and energy storage. These components and their control represent numerous opportunities for cost control, both in actual cost and in reliability, maintenance costs, and lifetime. Resilient control of the heliostat is required for adjustment of heliostat structure so it can accurately track sun position to reflect concentrated sunlight toward a receiver target. Wireless and closed-loop controls have become increasingly attractive for new installations as they offer potential cost savings and enhanced performance. In this project you are asked to improve a single heliostat structure, constructed in Phase 1, shown below, and you are also asked to select a method and design, construct and test a system that can accurately track sun position to reflect concentrated sunlight toward a receiver target.

https://www.energy.gov/eere/solar/articles/no-smoke-all-mirrors-developing-next-generation-heliostats

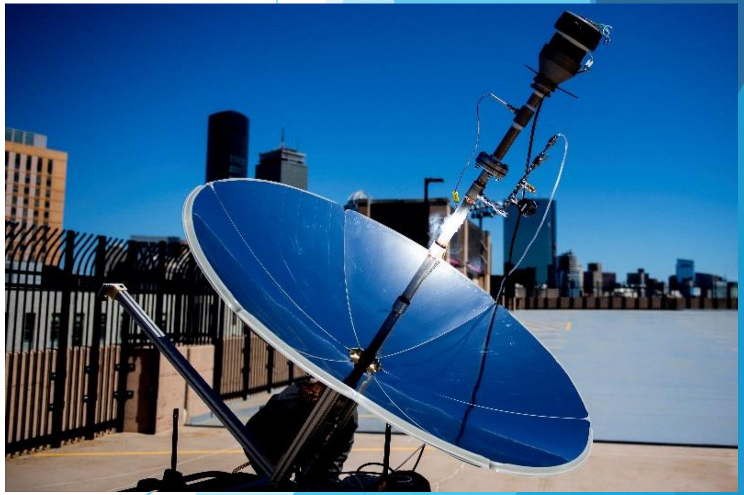
https://lm.solar/heliostats/

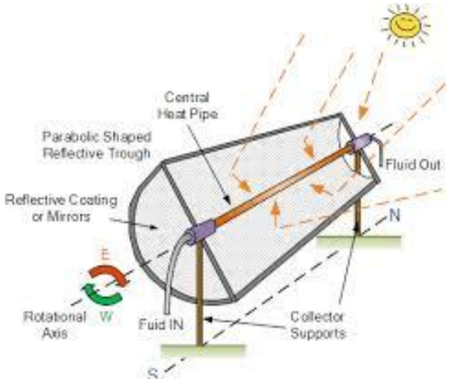
Solar pyrolyzer of pine needles to produce Bio-oil and biochar
Phase 2: use of a parabolic trough

Advisor: Yiannis A. Levendis y.levendis@neu.edu
Co-advisor: Greg Kowalski gkowal@coe.northeastern.edu

SUMMER I, 2024

- This project is related to forest fire prevention. Forest organic debris includes leaves, needles, snags, tree limbs and other dead organic material. Such material is highly flammable and contributes to the intensity and spread of forest fires. Removal of organic debris from forest floors can help minimize the spread of forest fires. The removal and collection of the debris can be incentivized by showing that it can be used as a feedstock for value-added products. The general idea proposed herein is to collect such organic debris form the forest floor and eventually pulverize it and utilize it as a bio-fertilizer, (a) in "as is" condition form, (b) as a bio-char, (c) as an activated carbon or (d) as combustion ashes. Bio-chars and activated carbons can be used as bio-fertilizers on various agricultural soils to improve the soil's chemical, physical, and biological properties, and increase crop productivity. The criterion for success will be to demonstrate enhanced growth of plants at the presence of bio-chars, activated carbons or bio-ash.
- In this project we will use waste dry pine needles as an example of such organic debris. You are asked to conduct a review of literature on this subject and design a ***continuous flow feeder for pine needles using a parabolic trough*** where this material can be pyrolyzed at high temperatures (300-600 °C). Phase 1 used a parabolic dish. Liquid bio-oil and solid biochar can be generated. Bio-oil can be collected, processed and used as a fuel. Bio-char can be further activated in steam and generate activated carbon, or it can be burned in air to generate ash. You may then use these materials to investigate their effects in aiding plant growth.





https://www.ene... articles/no-smoke-all-mirro... eneration-heliostats

Outcome from Capstone Courses

- CSP project are popular with the students, as are most renewal energy projects.

- Provides insight into what background students need to participate in CSP projects. Some of this information directly related to background topics in the course

- Two current capstone students have submitted posters to the AAAS (American Association for the Advancement of Science) competition based on their heliostat projects for 2024-25. Competition is in Boston, MA

- Second Capstone sequence has contacted us to participate as reviewers and experts.

- Benjamin Lynch has expanded his Capstone Design experience to enter the Masters ME program and the Gordon Engineering Leadership Program. Also, has a provisional patent

- Provided some interest in a Co-Op position at NREL and Sandia, not successful.

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LSAMP (Louis Stokes Alliance for Minority Participation) Summer Programs participation

Develop Co-Op opportunities

Heliostat mirror cleaning

study the state of the art in mirror cleaning systems and design a new system

Advisor: Hameed metghalchi metghalchi@coe.neu.edu
Advisor: Yiannis A. Levendis y.levendis@northeastern.edu
advisor: Greg Kowalski gkowal@coe.neu.edu

Summer 2023

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The reduction of the solar radiation input due to soiling of the optical efficiency of the heliostats in the solar field is a significant detrimental factor in concentrating solar power (CSP) plants. Please study existing methods and develop a design or method for a cleaning device. Build a scaled sized prototype to test your method.

https://www.osti.gov/servlets/purl/6867834

https://www.youtube.com/watch?v=XwKgrEWl07U

Heliostat mirror cleaning

study the state of the art in mirror cleaning systems and design a new system

Advisor: Hameed metghalchi metghalchi@coe.neu.edu
Advisor: Yiannis A. Levendis y.levendis@northeastern.edu
advisor: Greg Kowalski gkowal@coe.neu.edu

Summer 2023

Suggested Activities and Delivery ates:

Perform a literature search of existing cleaning techniques used in the heliostat field and for large photovoltaic installations

Solar energy backgrtound (start overview & incident solar radiation calculations (6/9) (6/15)

- “Renewable and Efficient Electric Power Systems, 2nd Edition”, Masters, 2013, John Wiley & Sons
- Solar Energy Engineering, Duffie, Beckman and Klein (Glazing surface (cover sheets) multiple reflections)
- Solar Energy Handbook - Jan F. Kreider, Frank Kreith
- Principles of Solar Engineering, Second Edition

What are heliostat systems/where are they located(6/2)

What techniques are currently used? (6/2)

What is the increase in performance (cost and energy factors) as a result of cleaning?(6/9)

What are the energy and cost factors for the cleaning process?(6/15)

Propose five different potential cleaning systems that could be used.(6/9)

Develop a set of criteria for evaluating these potential concepts.

Select one concept for prototyping a scale model; how would you test it?

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Short Course Development: Questionnaire developed by Gregory Kowalski and Rebecca Mitchell

Specify your level of interest in each course topic *

	I have no interest in this course	It's unlikely that I would take this course	I would take this course if it were convenient	I would likely take this course	I definitely plan on taking this course
What is CSP: An overview of the discipline and its advantages	○	○	○	○	○
Incident solar radiation prediction, ray tracing basics, losses, software available, and control needs	○	○	○	○	○

How many total hours are you willing to spend taking CSP online courses from October-December 2024? *

- ○ 1-5 hours
- ○ 6-10 hours
- ○ 11-15 hours
- ○ 15-20 hours

Sample above, three of 27 questions

Summary of Survey/progress

- Survey of Potential Participants (28 responded):
  - prerecorded videos/slide deck
  - Total course length: 25-28 hours, for five courses
  - Each course will be broken into 30-45 minutes segments
  - Introduction will be limited to 1 hour
  - Each segment may have a worksheet type of activity that will be submitted; ?should it be optional
- No clear feedback on official verification of course completion

Workshop I
Target Audience: Participants new to the CSP field with a technical background, wanting to enter it or in a technical policy field

- Introduction to existing facilities and general limitations and requirements (Chapt. 1)
- Characteristics of incident solar radiation: Design and operation perspectives (Chapt. 2 and supplement information)
- Energy vs Power considerations; load vs supply perspective
- Need for control strategies: not 1 mirror but thousands
- Need for energy storage
- Costs: Capital investment, land use area target, $/kWh
- The incident solar angle and reflection angle to receiver; an overview of the significant CSP problem.
- Receiver design considerations:

Workshop II Incident solar radiation prediction, ray tracing basics, losses, software available and control needs Target Audience: Participants newly hired in the CSP field or want a more detailed analysis (Have taken Workshop I)

- Details of Calculating incident solar radiation; Software presented
  - Design based
  - Operation based
- Ray trace basics; the real problem that needs to be address (Chapt. 3)
- Loss factors (Chapt. 3)
- Introduction of software [Solar Pilot and SolTrace as of now]
- How to provide the control of the heliostat field

Workshop III Receiver Design; basic design and numerical approaches
Target Audience: Participants in the CSP field or have taken Workshop II

- Receiver designs and working fluids
- Different Receiver designs (Chapt. 4)
- Material requirements: High energy flux and temperature, cost considerations (Chapt. 7)
- Include heat transfer basics, especially radiation transfer
- Present a typical "element" analysis that provides a background for most commercial codes (Chapt. 4) {This is really what goes into the commercial as an aide to understanding the need for specific boundary conditions and integration with the solar problem.
- Working fluid requirements: High energy flux and temperature, cost considerations; lifetime of working fluids and safety (Chapts. 5 and 7)

Workshop IV Energy Storage, need and cost factors
Target Audience: Participants in the CSP field with experience wanting more in depth simulation exposure for energy storage aspects or have taken workshop III

- Energy storage
  - Thermal storage related to salt and steam
  - Electrical storage
  - Other types of storage: bio stocks or waste to fuel
- Integrating solar models with thermal models and
- energy storage models
- Type of energy storage to respond to the load demand
- Microeconomics and thermoeconomics

Workshop V Production potentials what can we do with high temperature high heat fluxes
Target Audience: Participants in the CSP field who are interested in the manufacturing aspects or have taken workshop IV

- Electrical Power Production
- Synthetic Fuels from Hydrocarbon Resources (Chapt. 10)
- Solar Fuel Production by Thermochemical Dissociation of Water and Carbon Dioxide (Chapt. 11)
- Manufacturing Potential of Concentrating Solar Power

Thank you

Questions